Comparison of Torsional Vibration Measurement Techniques

Karl Janssens and Laurent Britte

Abstract Noise and vibration performance plays an important role in the development of rotating components, such as engines, drivelines, transmission systems, compressors and pumps. The presence of torsional vibrations and other specific phenomena require the dynamic behaviour of systems and components to be designed accurately in order to avoid comfort and durability related problems. This paper provides an overview of the instrumentation and challenges related to torsional vibration testing. The accuracy and performance of various measurement techniques are investigated by measurements on a Fiat Punto 1.4 l engine. The potential sources of error are discussed for each technique.

Keywords Torsional vibration testing · Measurement techniques

1 Introduction

With eco-engineering comes a new range of NVH issues to solve. New powertrain designs like start-stop systems, downsized engines, advanced torque lock-up strategies and the generic trend for weight reduction of the powertrain raise the importance of an in-depth understanding of torsional vibrations as they negatively impact comfort and ultimately engine and driveline efficiency. Torsional vibrations are of importance whenever power needs to be transmitted using rotating shafts or couplings, like is the case for e.g. automotive, truck and bus drivelines, recreation vehicles, marine drivelines or power-generation turbines.

Torsional vibrations are angular vibrations of an object, typically a shaft along its axis of rotation. As mainly rotational speeds are measured, torsional vibrations are assessed as the variation of rotational speed within a rotation cycle. These

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RPM variations are typically induced by a non-smooth driving torque or a varying load. Structural sensitive frequencies along a driveline may then amplify and transfer these phenomena, leading to comfort, durability or efficiency problems.

Despite tremendous progress in modeling accuracy, overall system complexity still necessitates accurate qualification and quantification of these torsional vibrations, under controlled or real-life operating conditions, in order to better understand and refine counter measures.

This paper provides an overview of the instrumentation and challenges related to torsional vibration testing. The accuracy and performance of various measurement techniques are investigated by measurements on a engine test bench.

2 Torsional Vibration Measurement Sensors

Various measurement techniques are available for torsional vibration testing. The best sensor can be selected for each individual case based on the physical quantity to be measured, the type of analysis, the accessibility of the shaft, the ease of instrumentation and the required accuracy.

2.1 Direct Measurements

2.1.1 Linear Accelerometers

Two linear accelerometers are fixed in a face-to-face configuration on the rotating shaft. The two accelerometers will measure the tangential acceleration. As they have opposite direction in the fixed system of the rotation axis, any translational acceleration of the shaft is cancelled by taking the average of both accelerometer signals.

Advantages:

- High dynamic range directly determined by the dynamic range of the accelerometers
- Low sensitivity to shaft translational vibrations when the accelerometers are well aligned.

Disadvantages:

- Expensive telemetry system or sensitive slip rings are needed to transfer the acceleration signals from the rotating shaft to the measurement hardware
- Mass loading for relatively small shafts influencing the structural behaviour of the shaft, e.g. causing torsional resonances to shift in frequency or shaft unbalance
- Bigger shafts at relatively high RPM cause centrifugal forces that may lead to dangerous loss of accelerometers and measurement equipment when not sufficiently well glued

- Since acceleration is measured, and angle and speed can only be derived by integration, no absolute angular position is available. Angle domain processing will not be possible.

2.1.2 Dual-Beam Laser Interferometers

Laser interferometers can be used as well to measure torsional vibrations. Laser manufacturers typically propose specific systems for rotating measurement based on dual beam techniques to cancel the effect of translational movement of the shaft. The angular velocity is computed from the velocity measured in the direction of the laser beams on the two pointed areas through the Doppler shift.

Advantages:

- Contactless measurement
- Low sensitivity to shaft translational vibration
- Low sensitivity to the shape of the shaft
- Easy instrumentation.

Disadvantages:

- Expensive device. Since it is often required to measure torsional vibrations at different shaft locations simultaneously, this is often a large drawback
- Exact angular speed and position are not known. Since velocity is measured, angle can only be derived by integration, no absolute position is available. Angle domain processing for example will not be possible
- The size of the device does not allow using it in a confined environment. Its use in real-life mobile conditions is very difficult or nearly impossible.

2.2 Coder-Based Techniques

Coder-based techniques make use of equidistantly spaced markers on the shaft or rotating component. The system measures every time a marker passes in front of a sensor and the time difference between two markers is used to estimate the angular velocity. The coder-based techniques have the advantage to deliver RPM and discrete angle position. The data resolution is determined by the number of markers: the more markers, the more accurate information.

Different types of coders are used, for example stripes drawn or glued on the shaft or the teeth of gears. Also different sensors are available to detect the markers, such as electro-magnetic pick-ups or optical sensors. Incremental encoders are devices combining the coder and sensor in one single hardware.

2.2.1 Magnetic Pick-ups

Magnetic pick-ups detect changes in the magnetic field or magnetic flux, typically resulting from metallic teeth passing the sensor. They are often used in industrial applications because of their robustness and low sensitivity to ambient dust. Set-ups for this are often very practical as well, since existing gear sets on the machine can be used as coder, e.g. the gear teeth on flywheels of transmissions. Resulting from that, magnetic pick-ups are very popular for measuring torsional vibrations, as they are easy to set up, as they work very well with existing gear teeth and as they are very robust. Most combustion engines today are equipped, by default, with these sensors to transfer the different shaft positions to the engine or gearbox controllers.

Advantages:

- Price. Mass production of magnetic pick-ups for automotive and industrial applications has a very positive influence on their end-user price
- Simplicity of instrumentation. The sensor is typically fixed on non-rotating components, which avoids the need for e.g. telemetry. Coders are mostly generated by existing gear sets
- Robust sensors with low sensitivity to ambient dust.

Disadvantages:

- The number of gear teeth sets limits to the number of pulses per revolution which could be insufficient to capture all torsional content
- The accuracy of the measurement is very much dependent on the machining accuracy and deformation of the gear teeth
- The sensor must be fixed very close to the rotating shaft which is sometimes difficult, e.g. when the shaft has an important translational movement
- Relative displacements between the magnetic pick-up and the shaft, due to shaft bending or due to displacement of the sensor attached on a too soft mounting, influence the quality of the measured pulses and generate a fictive torsional vibration.

2.2.2 Optical Sensors

Many types of optical sensors can be found on the market, however most of them are designed for object detection. To measure torsional vibrations, the sensor not only needs to be able to detect a high rate of events per second, also the timing accuracy of the detection is very important and this accuracy is often insufficient.

Optical sensors generate an electric signal proportional to the received light intensity. Optical fibers are used to conduct the light from the emitter to the sensor head and back from the sensor head to the receptor. They can be configured in reflection or transmission configuration.

Optical sensors can be used with many different types of coders as long as the visible contrast between the stripes is sufficient. Most optical sensors deliver a TTL output signal.

Advantages:

- The instrumentation is very simple as the sensor is typically fixed on non-rotating components. Only the coder needs to rotate.
- Optical sensors can be directly instrumented on gears as is the case with magnetic pick-ups, under condition that the reflection of the material gear surface is sufficient
- Coders can easily be implemented on shafts with contrasted paint or zebra tape
- The fast response and good phase accuracy of high-quality optical sensors allow the measurement of very high pulse rates.

Disadvantages:

- The sensitivity to ambient light and/or the quality of the material reflection complicate the direct instrumentation of the gears in gearboxes
- The sensor must be fixed very close to the rotating shaft which is sometimes difficult when the access is limited or when the shaft has some translational movement
- Relative displacements between the optical sensor and shaft influence the quality of the measured time stamps and lead to torsional vibration measurement errors.

Black and white tapes are more and more used to quickly implement a coder on a shaft. They can be used to create a coder when no gear wheel is available or when a higher number of pulses per rotation is required. There are two families of tape depending on whether it must be glued around the shaft (zebra tape) or on the extremity (zebra disc). Zebra tapes and discs exist in multiple stripe width to adapt the number of pulses per revolution in function of the shaft diameter.

Although zebra tape is very easy to instrument, an error will be introduced onto the measurement at the location where the two zebra tape endings come together. When this point passes the optical sensor it will introduce a discontinuity in the RPM signal. A butt joint correction should therefore be applied before analysing the measurement signal (Janssens et al. [1]).

Zebra discs do not suffer from this butt joint problem, however proper care needs to be taken to properly center the disc. Since perfect centering is never possible, torsional order 1 is typically not reliable when using this coder set-up.

2.2.3 Incremental Encoders

Incremental encoders are devices typically used in automat or robotic applications for accurate detection of shaft positions. Their high accuracy makes them very attractive for torsional vibration analysis applications as well. Often based on optical technology, incremental encoders combine the coder and the sensor in one single device. They consist of both a rotating (rotor) and static (stator) component and the full sensor needs to be mounted on the set-up. Incremental encoders come in many different shapes and sizes, to cover all required applications.

The incremental encoder makes use of three embedded coders: one detecting one single pulse per revolution, called index, as absolute angle reference and two more high resolution encoders called A and B. The A and B signals have exactly the same number of pulses but the B signal is phase shifted with a quarter of a pulse cycle (90°) compared to A. The combination of these two coder signals allows detecting the sense of rotation of the coder.

Advantages:

- The fully integrated approach allows developing accurate coders with potentially very high pulse rate. Incremental encoders can be delivered with the appropriate number of pulses, depending on the application and desired accuracy typically 50–500
- The sense of rotation can be a great advantage, e.g. for the investigation of the start/stop behaviour on engines
- The integrated index signal allows duty cycle related analysis with accurate TDC identification (e.g. engine combustion analysis).

Disadvantages:

- The relative complex instrumentation limits their usage for in-vehicle or mobile measurements. Incremental encoders are mainly used when working on test benches where the instrumentation makes part of the test bench equipment.

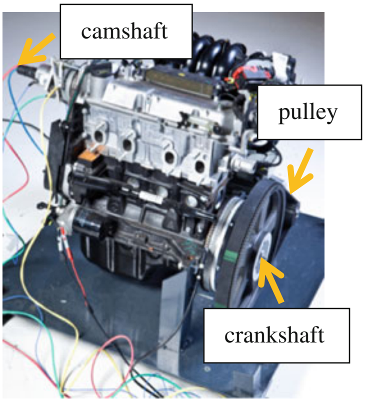
3 Test Campaign

3.1 Test Set-up

An experimental test campaign was carried out on a 4-cylinder Fiat Punto 1.4 l engine (Fig. 1 left). The engine was driven by an electric motor controlling the speed profile. The engine crankshaft and electric motor were connected by a pulley. Torsional vibration measurements were conducted on the camshaft (Fig. 1 right). The shaft was instrumented as follows:

- Dual beam laser (RLV 5500 Polytec system)
- High speed incremental encoder (Heidenhaim ROD 426, 1,024 pulses per rev)
- Zebra tape (142 stripe pairs, 1 mm stripe width, Optel Thevon optical sensor)
- Zebra disc (120 pulses per revolution, Optel Thevon optical sensor).

Various constant speed and run-up tests were carried out in the following two conditions: (1) 4 cylinders open (spark plugs removed): rather small torsional



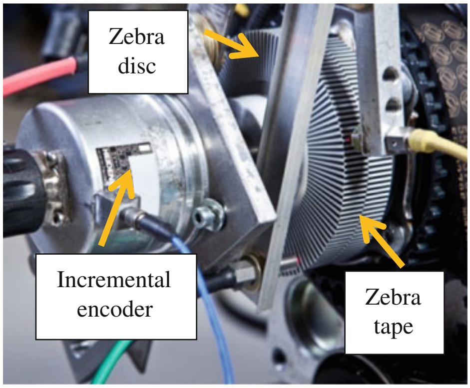


Fig. 1 Fiat Punto engine set-up (*left*), instrumentation of camshaft (*right*)

content related to the piston movements; and (2) 1 cylinder closed: large torsional content due to the high pressure changes (compression and expansion) in the closed cylinder, once per rotation of the camshaft.

3.2 Test Results

3.2.1 Four Open Cylinders

Figure 2 shows the RPM-frequency colormap of the torsional vibration measurements on the camshaft by the dual beam laser, incremental encoder, zebra disc and zebra tape in a run-up test with 4 open cylinders. There is obviously a good match between the analysis results within a 30 dB dynamic range. The dominant orders 4, 12 and 16 are well captured by all methods. Only slight differences are noticeable for the less significant orders. The zebra disc results are of lower quality in the 70–90 Hz frequency range, possibly due to the vibrations of the optical probe which is not idealy fixed. One can also notice that the zebra disc is not perfectly centered on the shaft, causing an order 1 misalignment error.

Figure 3 shows the amplitude and phase profile of torsional orders 4 and 16 as obtained with the 4 measurement techniques. There is a good match in amplitude and phase all along the RPM axis, even when the order becomes less important with amplitudes lower than 0.01°.

Figure 4 compares the RPM time variations obtained from the zebra tape measurements with those of the incremental encoder before (lower graph) and after (upper graph) application of a zebra tape butt joint correction. The spikes in the RPM data are clearly removed, illustrating the effectiveness of the correction method. The corrected zebra tape measurements and incremental encoder RPM data match very well.

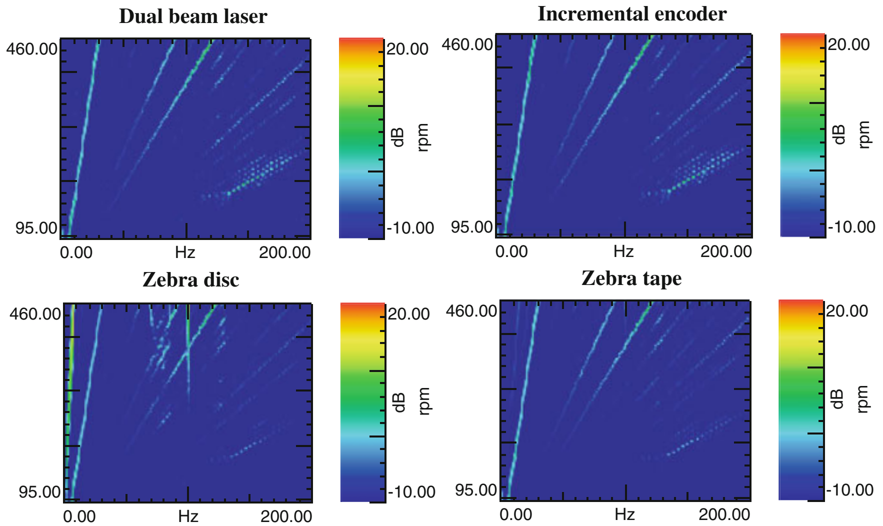


Fig. 2 RPM-frequency map of camshaft torsional vibration measurements in run-up test with 4 open cylinders

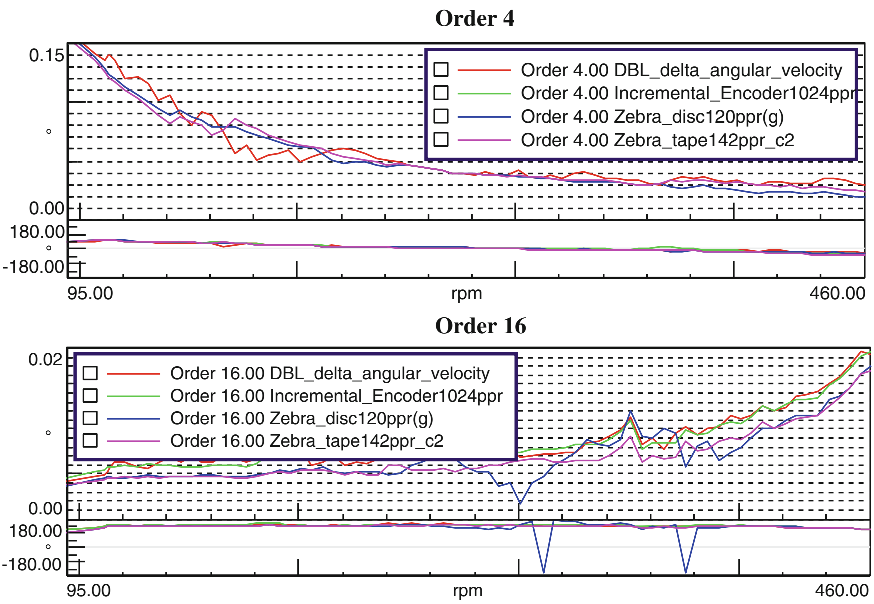


Fig. 3 Camshaft torsional order cuts in run-up test with 4 open cylinders

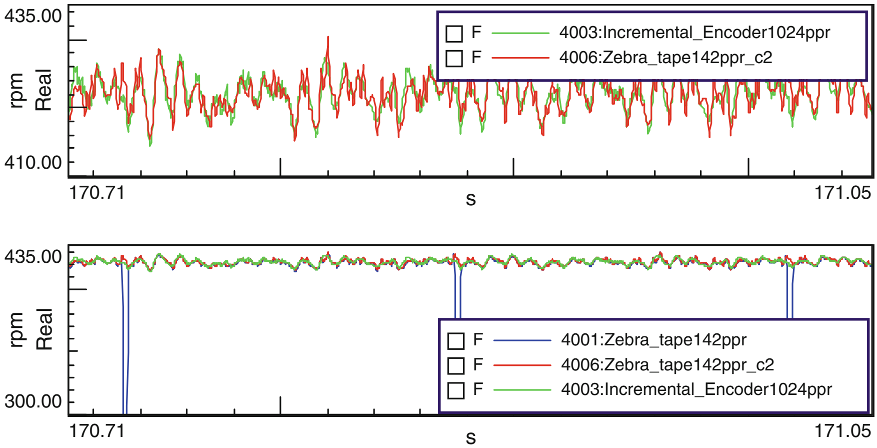


Fig. 4 Camshaft RPM fluctuations measured with zebra tape (with and without butt joint correction) and incremental encoder in a test with 4 open cylinders

3.2.2 One Cylinder Closed

The torsional vibration results for a run-up test with 1 cylinder closed are shown in Figs. 5, 6, and 7. The large pressure changes (once per camshaft revolution) in the closed cylinder cause strong RPM variations which are clearly visible in Fig. 5. The large RPM drop every rotation yields multiple torsional orders as shown in Fig. 6. Here again, the torsional vibration results of the 4 measurement methods are similar within the 30 dB dynamic range. This is also clear from the order sections in Fig. 7, showing a similar amplitude and phase profile.

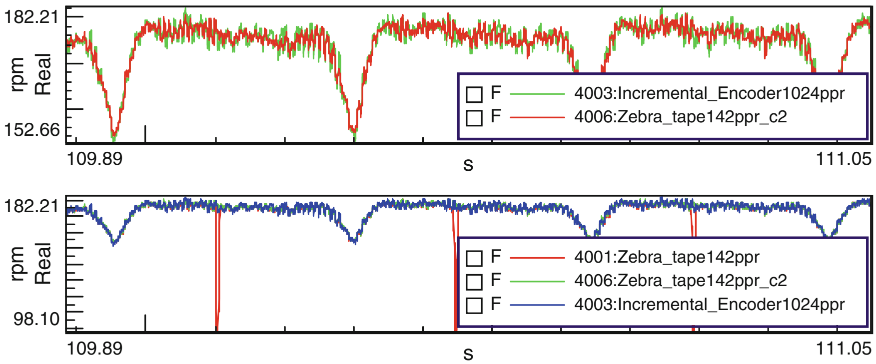


Fig. 5 Camshaft RPM fluctuations measured with zebra tape (with and without butt joint correction) and incremental encoder in a test with 1 cylinder closed

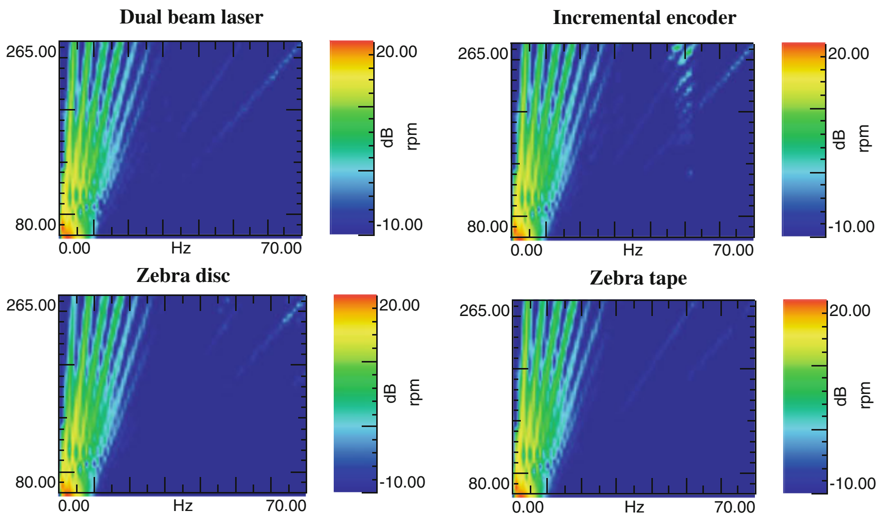


Fig. 6 RPM-frequency map of camshaft torsional vibration measurements in run-up test with 1 cylinder closed

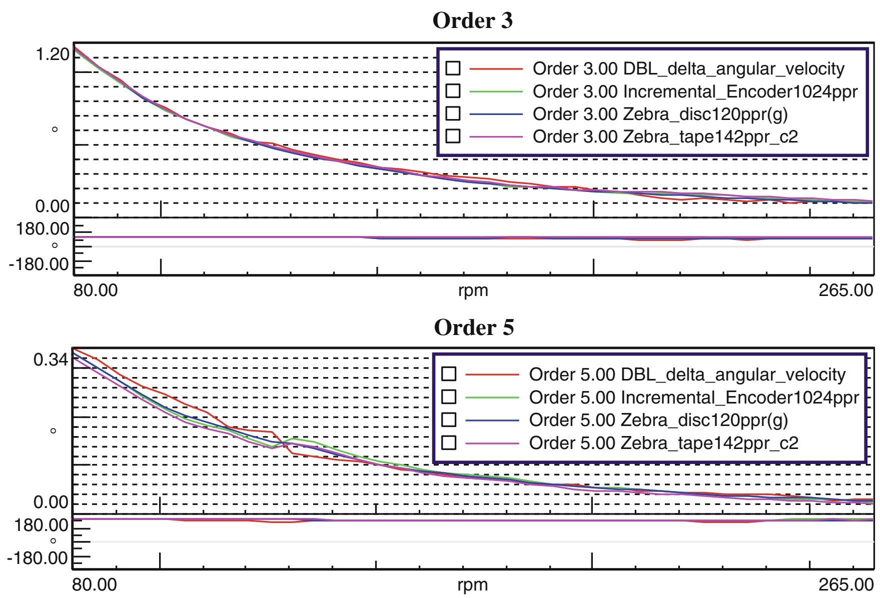


Fig. 7 Camshaft torsional order cuts in run-up test with 1 cylinder closed

4 Conclusions

It is known since a long time that the dual beam laser and incremental encoder are good and accurate measurement techniques for torsional vibration testing. However, the set-up space of the laser system and relative complex instrumentation of the incremental encoder limit their usage for in-vehicle and mobile measurements. Zebra tape and disc measurements do not suffer from these limitations which is obviously a benefit. Next to this, they also perform well in terms of accuracy. With various experimental tests on a Fiat Punto engine, we have demonstrated that the torsional vibration results obtained with these measurement techniques correspond very well to those of the dual beam laser and incremental encoder.

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